Optimisation of a SiW–ECAL resolutions for Higgs Factory

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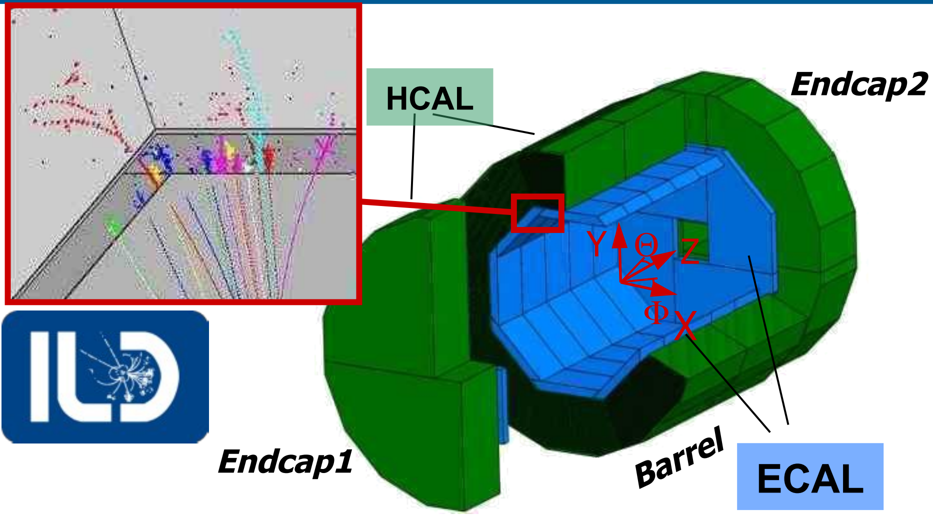
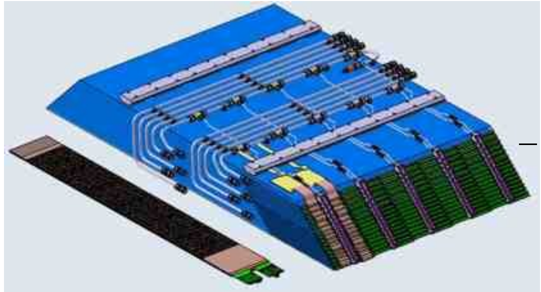
ECFA e+e– WS, DESY, 06/10/22

An Ultra-Granular SiW-ECAL for experiments



Particle Flow optimised calorimetry

- Standard requirements
  - Hermeticity, Resolution, Uniformity & Stability (*E*, *(θ,φ)*, *t*)
- PFlow requirements:
  - Extremely high granularity
  - Compacity (density)



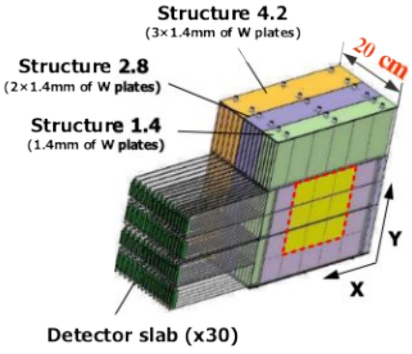
SiW+CFRC baseline choice for future Lepton Colliders:

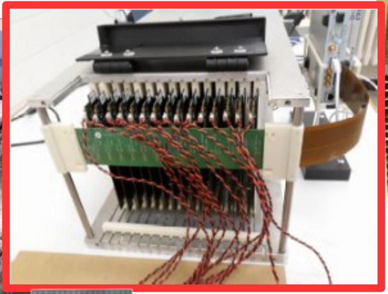
- Tungsten as absorber material
  - X_0 = 3.5 mm, R_M = 9 mm, λ_I = 96 mm
  - Narrow showers
  - Assures compact design
- Silicon as active material
  - **Support compact design: Sensor+RO≤2mm**
  - Allows for ~any pixelisation
  - Robust technology
  - **Excellent signal/noise ratio: ≥10**
  - **Intrinsic stability (vs environment, aging)**
  - **Albeit expensive…**
- Tungsten–Carbon alveolar structure
  - **Minimal structural dead-spaces**
  - **Scalability**

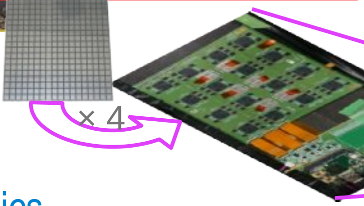
To be assessed by prototypes

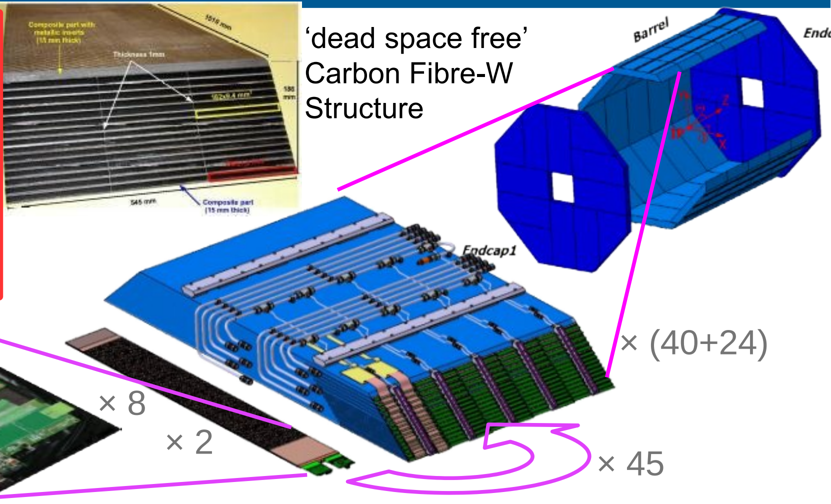
Not included: general services

CALICE prototypes for ILC / HF









Physical (2005-11)

– 1×1 cm² on 500μm 6×6 cm² Pad glued on PCB Floating GR
– × 30 layers (10k chan).
– External readout
– Proof of principe

Technological (now)

– Embedded electronics
  - Power-Pulsed, Auto-Trig, delayed RO
  - S/N = (MPV/σ_{Noise}) ≥ ~12 (trig)
– Compatible w/ 8+ modules-slab
– 5×5 mm² on 320–650μm 9×9 cm² × 26–30 layers
  - 8k (slab) ~ 30k (calo) channels

Pilote ➡ Full Detector

– 1M ➡ 70M channels
– on 750μm 12×12 cm² 8" Wafers ?
– Pre-industrial building
– Full integration (⊃ cooling)
– Final ASIC

We are here

Rationale/Questions

PFA combines : particles to get the best possible Jet Energy Resolution (JER):

- Charged Particle ~65% of E
- Long Lived Neutral Hadrons ~ 10%, measured by ECAL+HCAL
- Photons: 27 % E, solely measured by ECAL ← **how well are those measured ?**
- Separation of close photons, photon/charges (τ and π^0's tagging)

How can we improve the resolution… ?

- Lower E–gamma threshold
- "Best" E-resolution ← that depends on the average energy of the photons

… while keeping the cost and reasonnable and technical feasibility

- Contants: number of layers, amount of tunsgten

Parameters space

Main parameters of the ILD SiW-ECAL

- 24 X_0 of W
- 15 layers (CALICE proto) / 30 layers (ILD)
- 2 sections of 1 and 2 thickness of W
- Cell size of $(5.5\ mm)^2 \times 500\ \mu m$

Boundaries: What needs to be fixed ?

- Cost ?
- Min. Performances

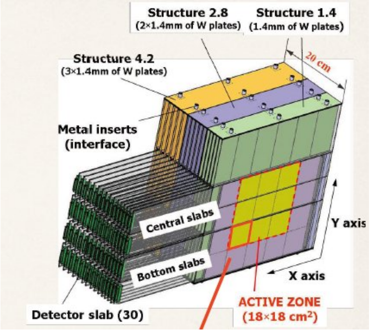
Each needs introspection

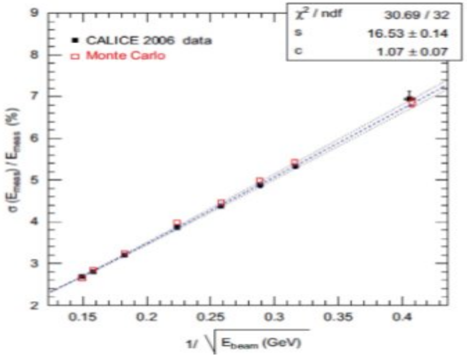
- Optional W thickness ?
  - Photon (and Electron) containment
    - Highly dependant on E tails and angles
- Optimal number of layers ?
  - More is better…
  - Upper limits from cost and heat
  - Lower limit from performances
- Absorber repartition: ~ started
  - Unhomogenous might bring longitudinal dependance of E
- Cell size: studied (PFA, CALICE prototypes)
  - To be reassesed for circular colliders

Previous studies

CALICE physical prototype:

- $(1\text{ cm})^2$ cells × 30 layers NIM A608, 372–383 (2009)
- 3 sections
- sampling fractions ω (× odd/even)
- $E_{\text{rec}}(\text{MIPs}) = \sum_i w_i E_i$

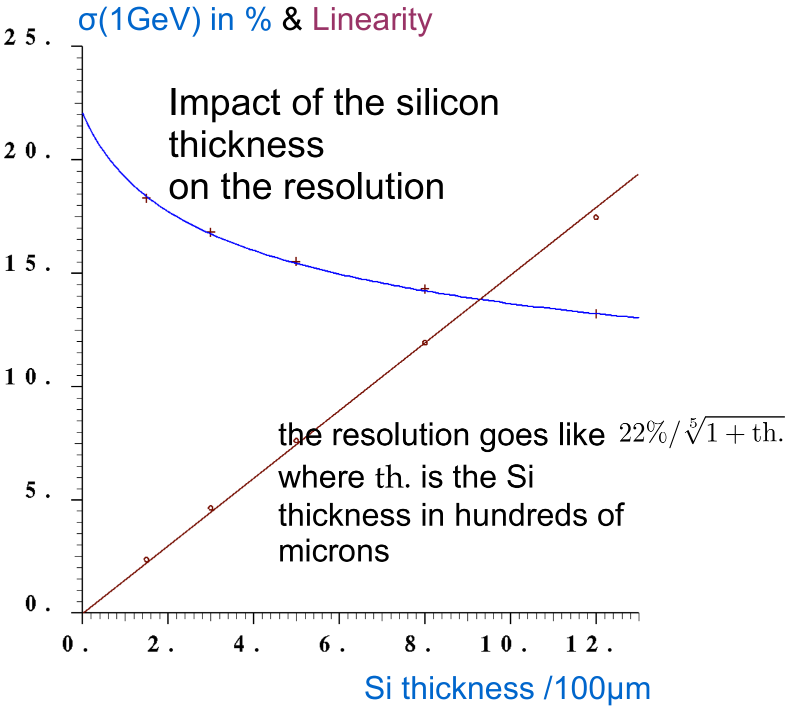




16.5%(stochastic) 1–2% (constant) obtained with 1–45 GeV e^-/e^+ at 2006/2008 BT

Sampling Fraction (H. Videau)

- E_{rec} for various Silicon thickness



Previous studies

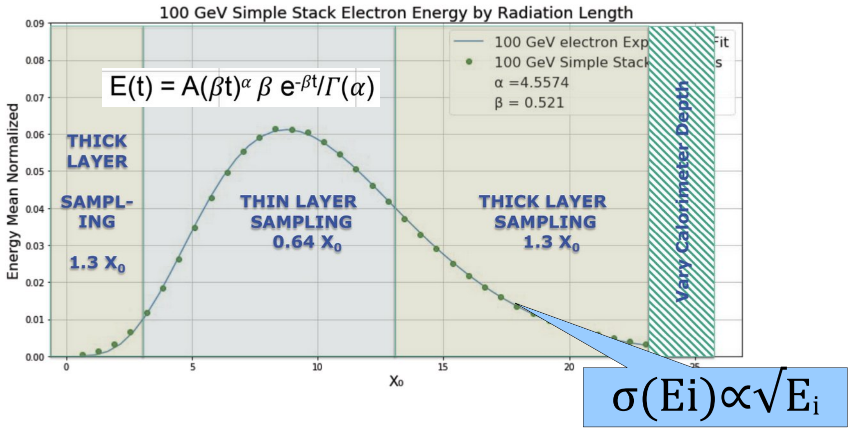
SiW ECAL Fast Sim Studies

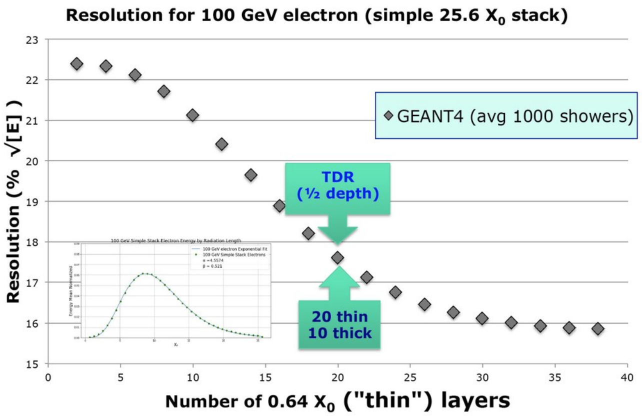
– Thin W : 20× 0.64 X_0

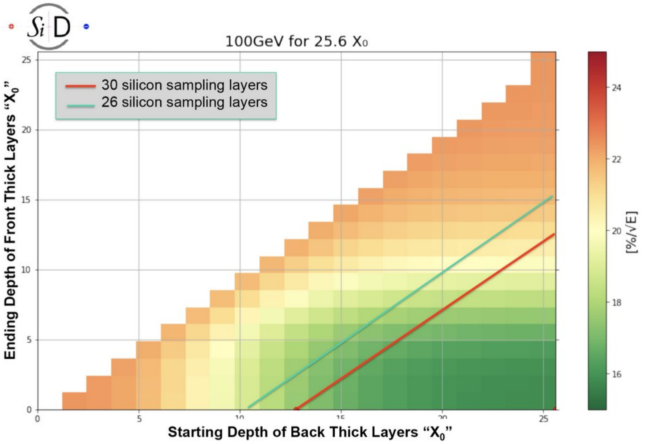
– Thick W: 10× 1.3 X_0

– 13 mm² Hex pads

J. Brau, LCWS 2018





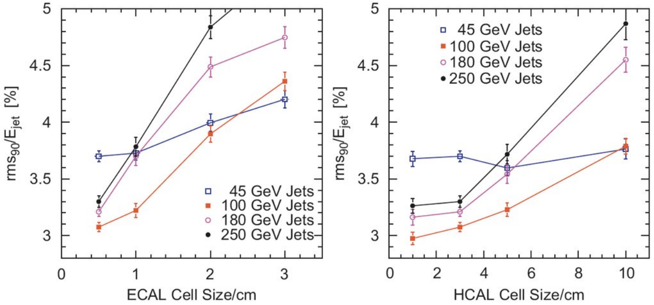


Previous studies: PFA

PandoraPFA Studies

NIM A611 25-40 (2009)

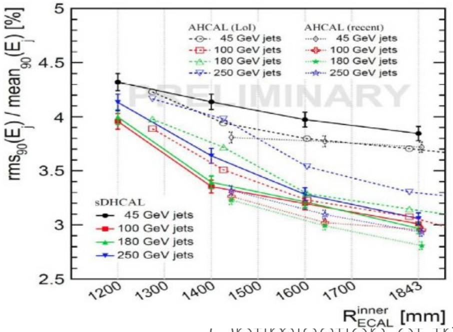
- JER Optimisation vs
  - Radius, cell size, B
  - Scint HCAL



- Radius with SDHCAL

ArXiv: 1404.3173

  - vs Radius, B



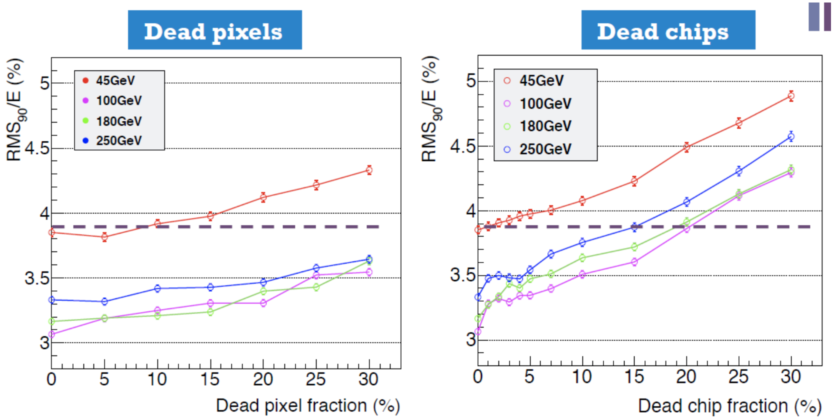
- Others…

ILD: Robustness of a SiECAL used in Particle Flow Reconstruction

- Jet Energy Resolution vs
  - dead channels, noise, mis-calibration and cross-talk
  - using PandoraPFA

ArXiv:1404.0124

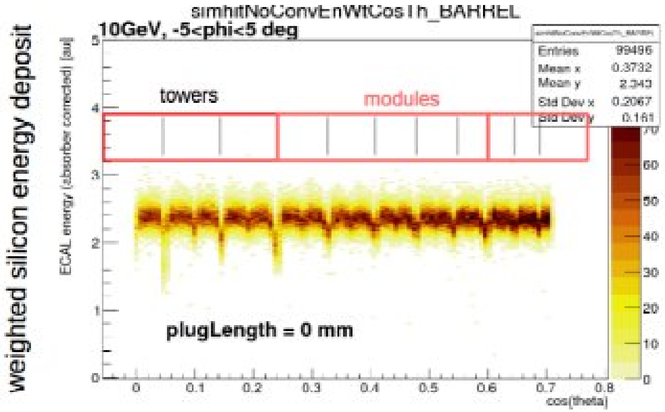
JER

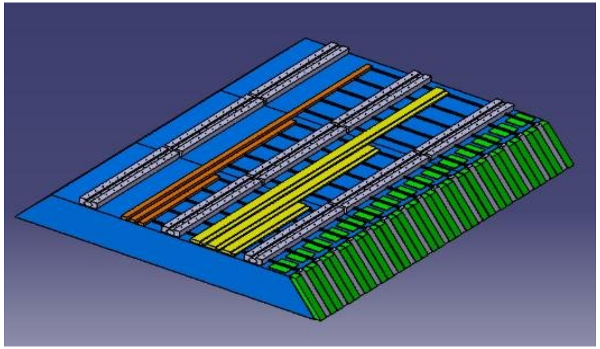


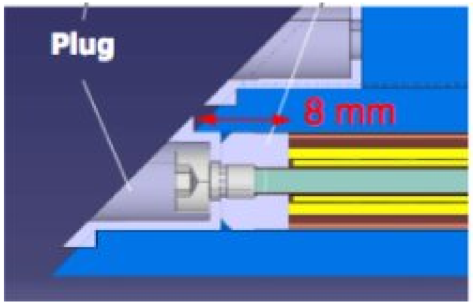
Specific studies

Dead materials

- ILD: . Jeans



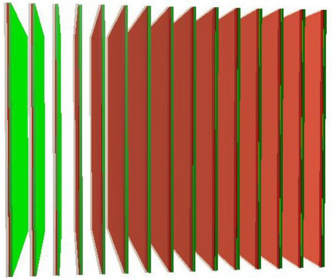


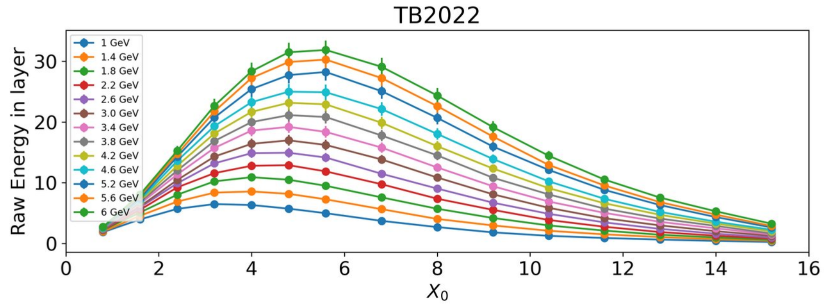


EM shower in Highly-Granular ECAL

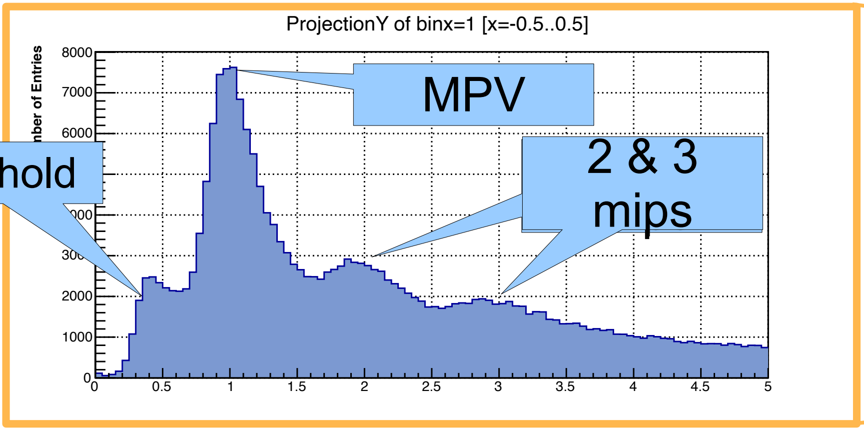
As illustration:
Full Simulation of
SiW-ECAL prototype
(DD4Sim)

- 15 layers × $(5.5\ mm)^2$
  - Silicon Sensors 500 µm + 650µm
  - W of 7× 4.2 mm ($1.2X_0$) and 8× 5.6 mm ($1.6X_0$)
    - ≠ ILD but easy modifications
- Calibration on muons

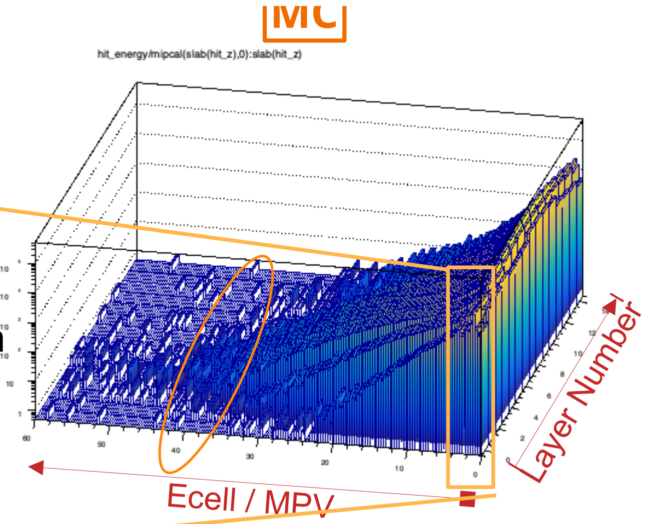




F. Jimenez



3 GeV electrons energy deposited in $(5.5\ mm)^2$ cells



Escale → ≤ ~40 mips / cells

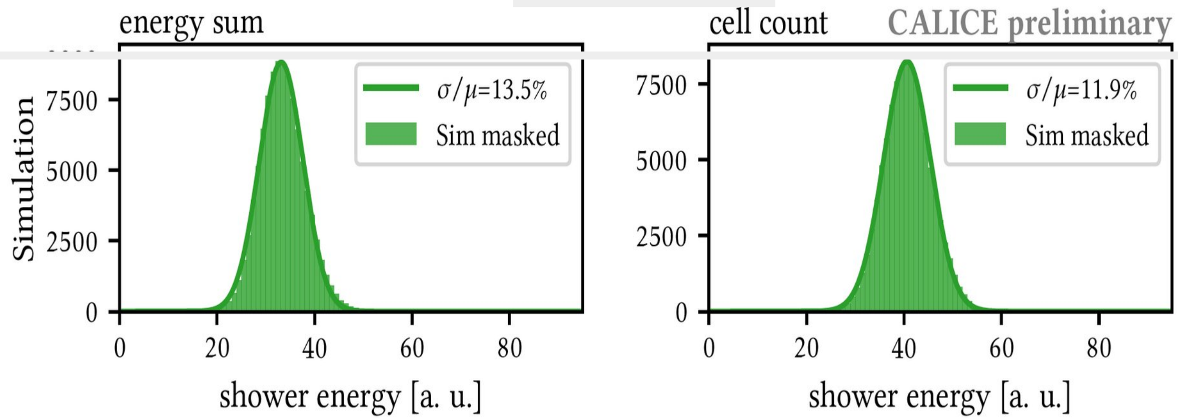
Energy measurements

Energy reconstruction

Energies

- $E_\Sigma = \sum E_i$
- $E_f = \sum \omega_i E_i$; $\omega_i = 1/(1+f_i)$;
  $f =$ mip sampling fraction
- $E_h = \sum (E_i > 0{,}5 \text{ mips})$
- $E_{fh} = \sum \omega_i \times (E_i > 0.5 \text{ mips})$

3 GeV electron

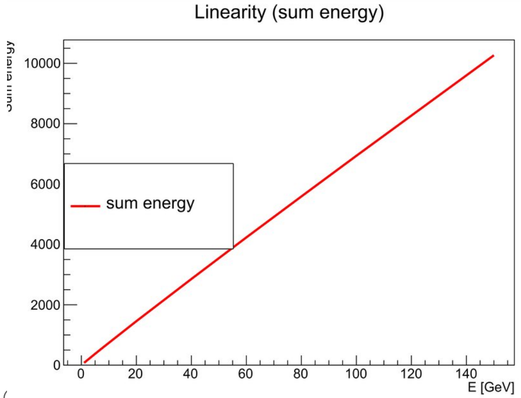


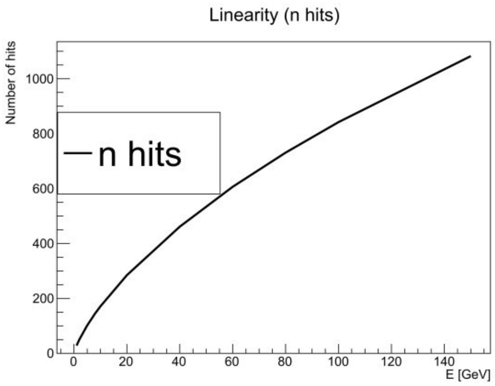
J. Kunath, F Jimenez

Nhits E_h

At least as regular as energy…

… but saturates at high energy.





Energies Resolutions

Preliminary resolutions

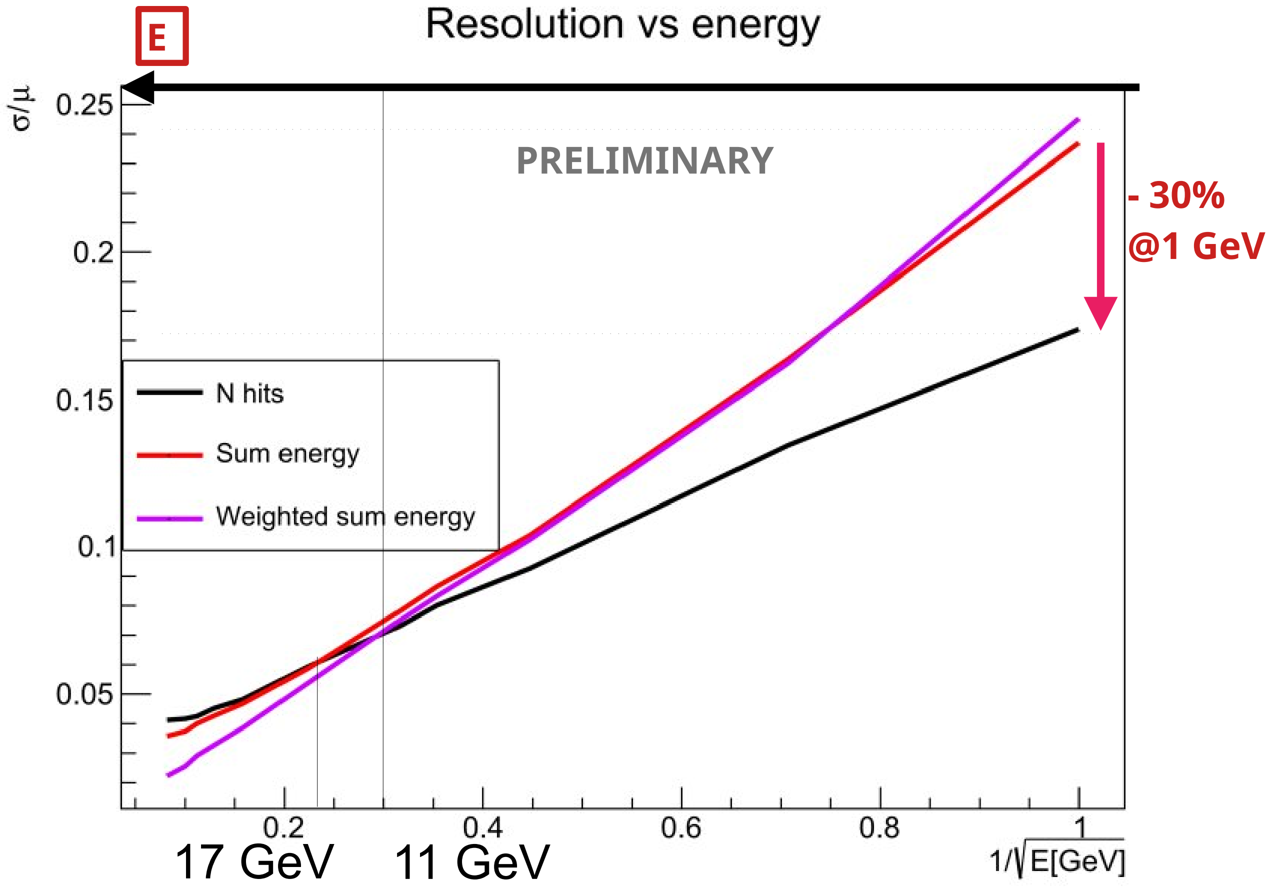
- Linearity corrected
- Errors bars within the lines
- No digitization, No clustering, No noise
  - But cut at 0.5 mips
  - Small incidences expected

E_Σ and E_f :

- Nearly identical
  - little difference between sections

E_h :

- (Significant) Improvement ≤ 11 GeV
- Possible explanation:
  cutting out Landau fluctuations

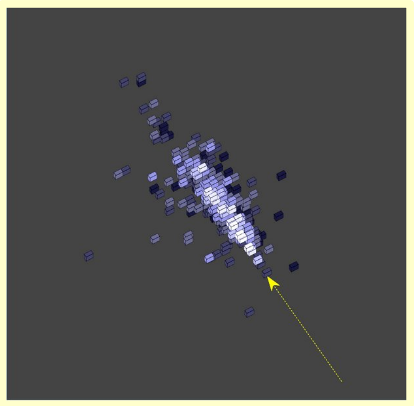
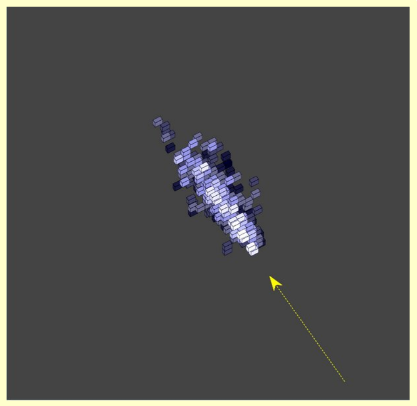


Previous work

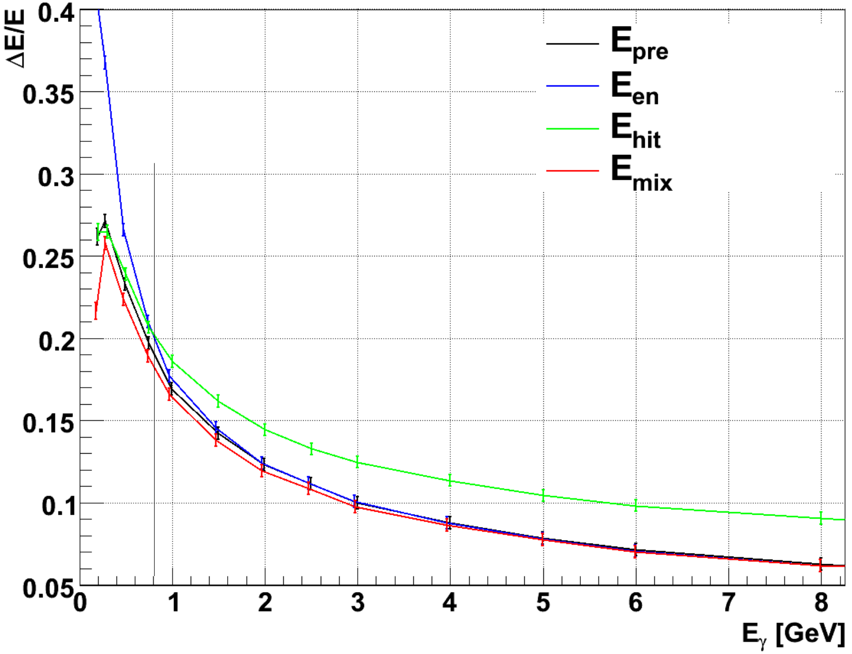
M. Reinhard PhD (2009, adv: J-C Brient)

$$E^{en}_{meas} = \alpha(f_1 E^{even}_1 + (1-f_1)E^{odd}_1) + \beta(f_2 E^{even}_2 + (1-f_2)E^{odd}_2)$$
$$E^{hit}_{meas} = \gamma N_1 + \delta N_2$$

- On ILD SiW-ECAL
  - $(5mm)^2$ cells, 2 sections
- GARLIC clustering (cleaning of outlier hits)

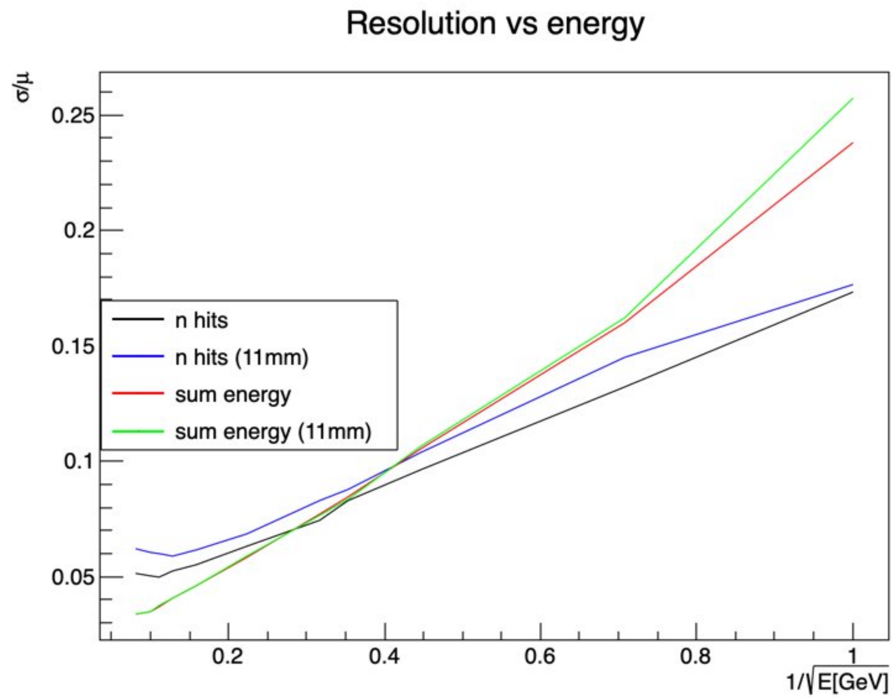



- Not obvious in all regions
  - overlaps, gaps, …

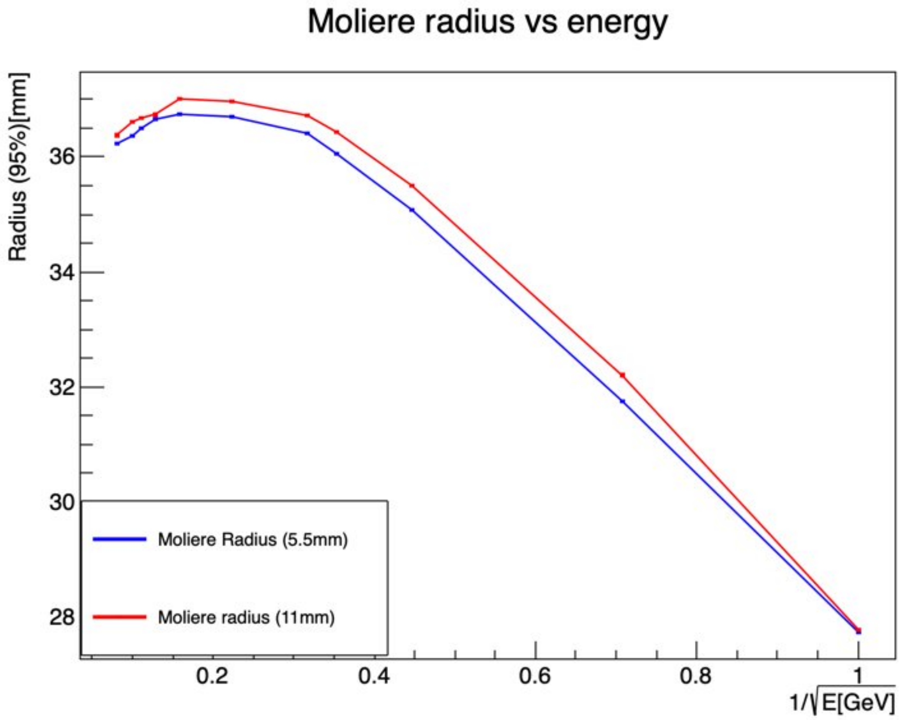


Molière Radius & Cell size

Resolution for 11 and 5.5 mm



Molière Radius for 5.5 and 11 mm

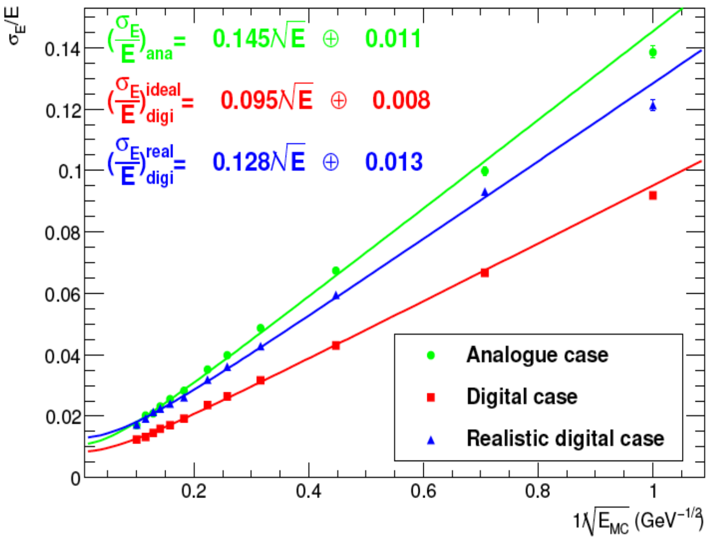


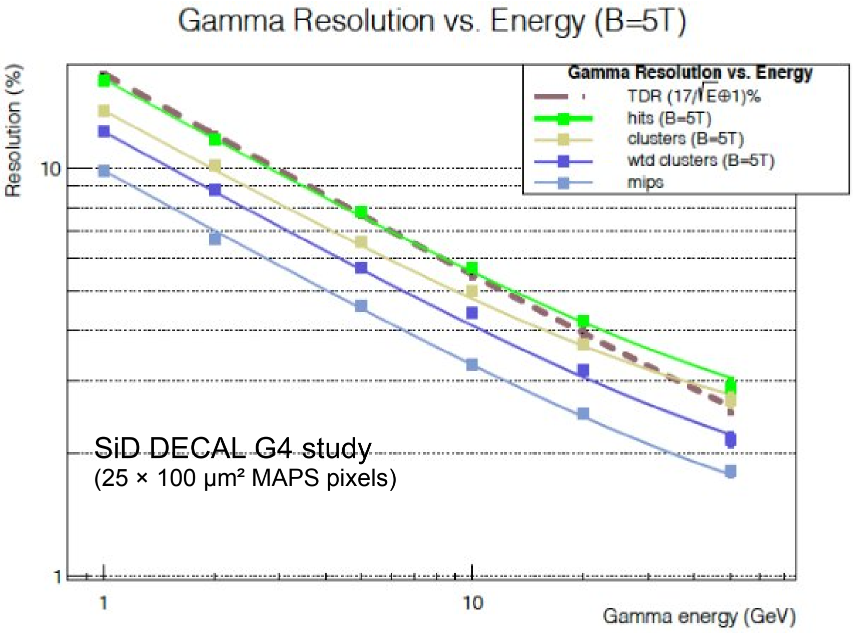
Ultimate Granularity ?

Studies by SID ECAL group (2021)

- Large area MAPS
- Pixels of 50×50 µm² or 25×100 µm²

arXiv:0901.4457

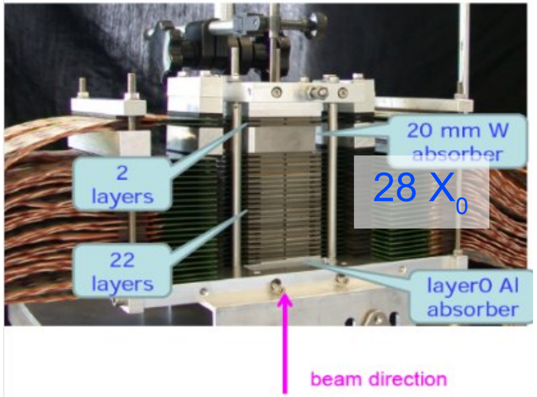


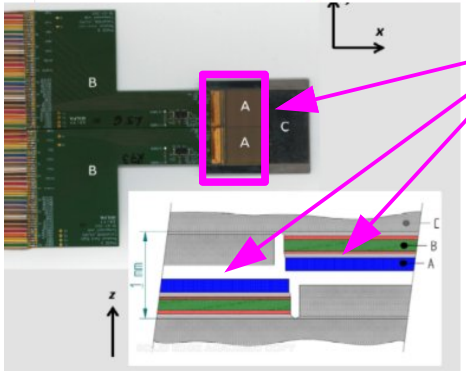


Updating the SiD Detector concept arXiv:2110.09965

MAPS & DECAL

FOCAL DECAL prototype





4 MIMOSA-26 / Layer
CMOS sensors (IPHC)

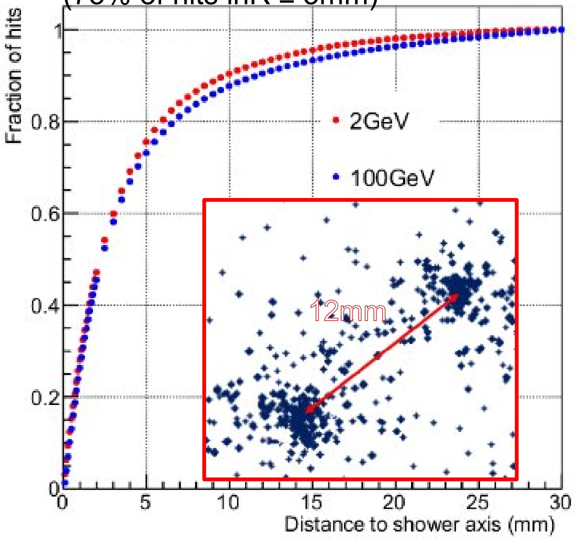
- 6×6 cm²
- 30×30 µm² pixels
- 39 M pixels
  = full readout

FOCAL = 2 layers of MAPS

but How to build a full detector ?

- Services: Power + Cooling ?
  - Gains by going fully digital ?
- For what physical gain ?
  - Improved separation ✓
  - Improved resolution ?

R_M = 10.5mm
(75% of hits inR ≤ 5mm)



Technical feasibility

Detector optimisation for Higgs Factories

Continuous running ≠ Pulsed runnning

– Power × 100 !

Low energy (90 GeV)

– Lower energy – less focused jets

- Lower granularity needed (1–2 cm OK ?)
- Lower dynamic range

– Other criterions ? Tagging

… but not so for the rest (≥ ~250 GeV)

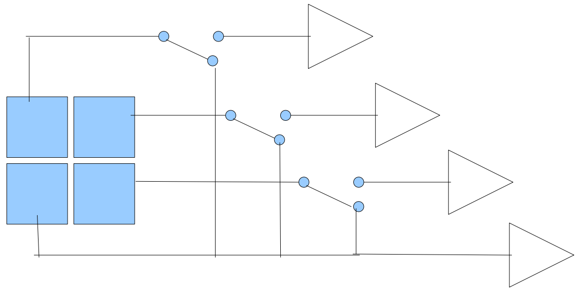
Reduce the number of layers + thicker sensors

– See “Small ILD” model

– 6’’×500μm wafers ➡ 8’’ × 725 μm (resolution $1/\sqrt[5]{d}$)

One size fit all ?

– Have a dynamic granularity ?



– Have a semi-digital readout ?

- Hit counting for low energy
- E measurement for high energies

Conclusions

SiW-ECAL's parameters can probably be optimized

- For single photons
- For photons in Jets (with clustering)
- For Tau decays
- For Particle ID (with timing)
- For pointing (Long Lived Particles)

DD4Sim model for CALICE prototype(s) Nearly ready:

- Flexible Geometry ✓
- Cell masking ✓
- On-going : digitization ↔ Data

Energy reconstruction with high-granularity started on single electrons

- Energy estimators can be improved
  - by Machine Learning (HGCAL)
  - by brain (current work)
- Hit counting seems reliable for low (≤15 GeV) electrons.
- Needs combination of different E's measurement

Next Steps:

- Confirm results with digitisation, on photons
- Detector optimisation by varying absorbers repartition
  - at fixed $\sum X_0$ and number of layers

Bonus

Reduced number of Layers

Going from 30 to 22 layers

- Reduction of cost; (small) reduction of R_M ; increase of Energy resolution
  - "better separation at the expanse of the intrinsic resolution"

Increasing the Si thickness to 725µm, if really feasible (next slide)

Energy resolution σ(E)/E:

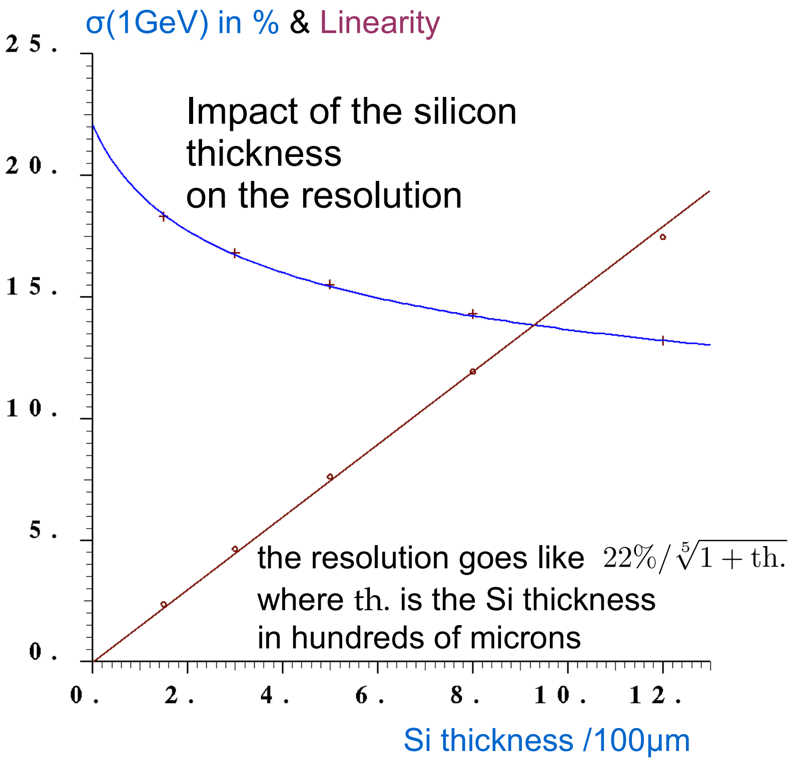
- for 22 layers w.r.t. 30: +16.8%
- with 725µm w.r.t 500µm : –6.1%

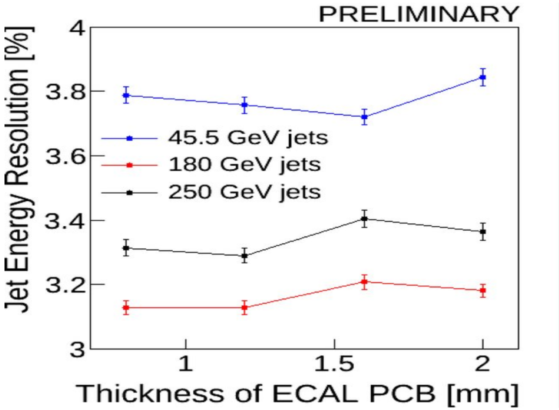
ECal thickness = 190.1 mm (close to 185 mm of DBD).

- 22 layers = 14 layers with 2.8mm thickness
  + 8 layers with 5.6mm shared between structure and slabs.

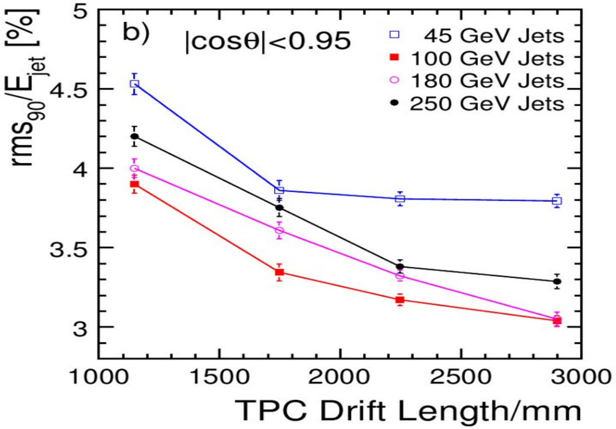
Study needed on separation, resolution and efficiency performances at low energy.

- JER : $\sigma(E_J)/E_J$ +10% for 20 layers (500 µm).

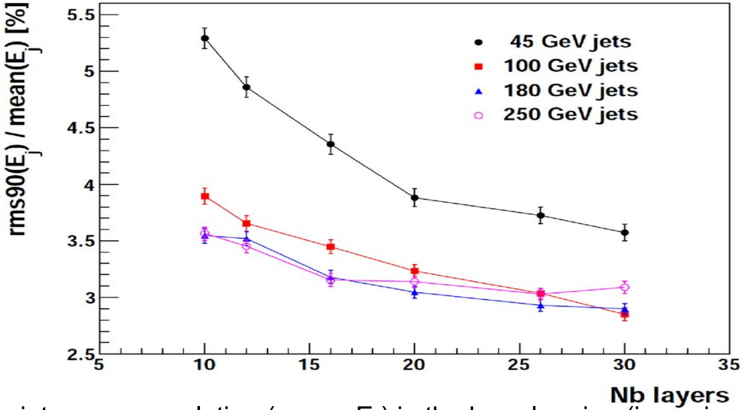




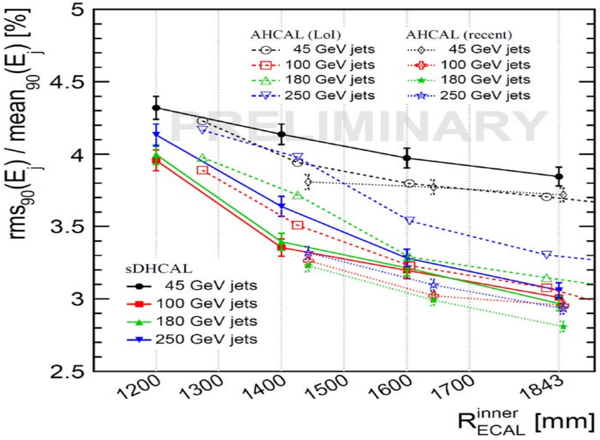
Single jet energy resolution as a function of the thickness of PCB with embedded electronics.



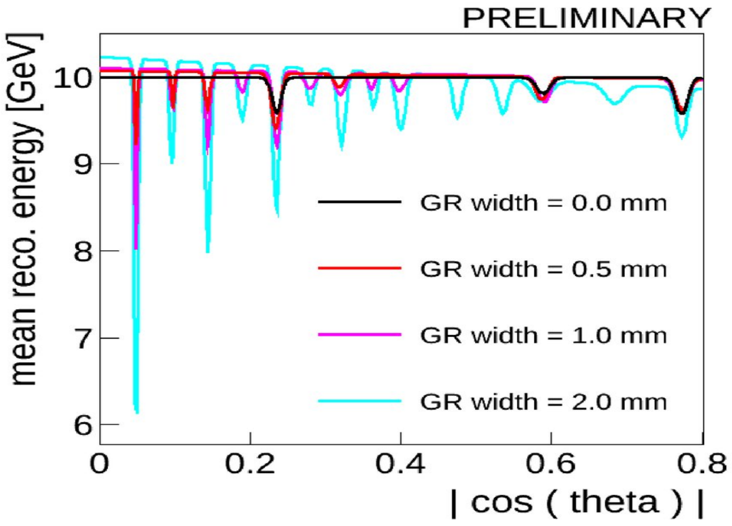
Single photon energy resolution as a function of the number of silicon layers for four photon energies.

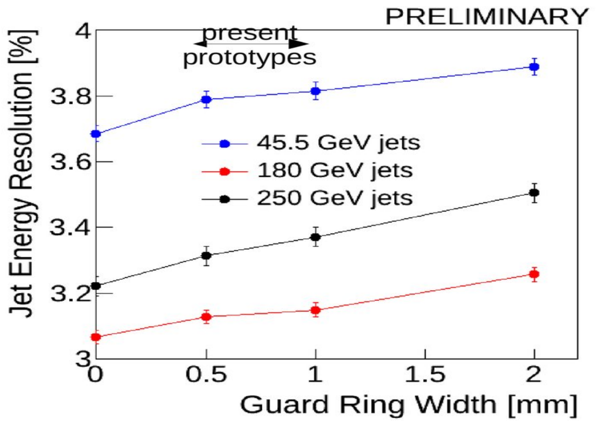


Single jet energy resolution (rms90=E) in the barrel region (j cos j < 0: 7) as a function of the number of ECAL silicon layers in events e+e-→ ZX → usd



ILD jet energy resolution in the barrel region j cos j < 0: 7 as a function of its radius.

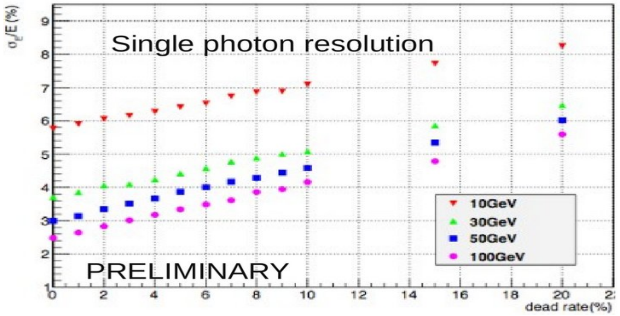


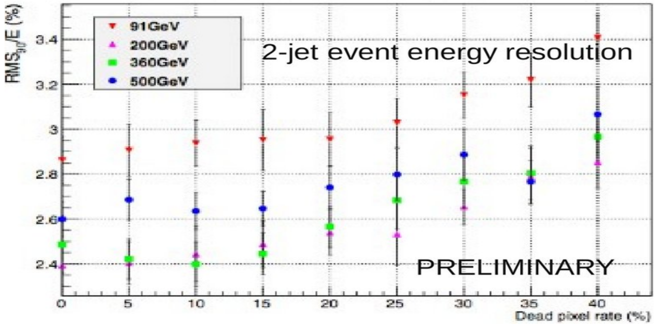


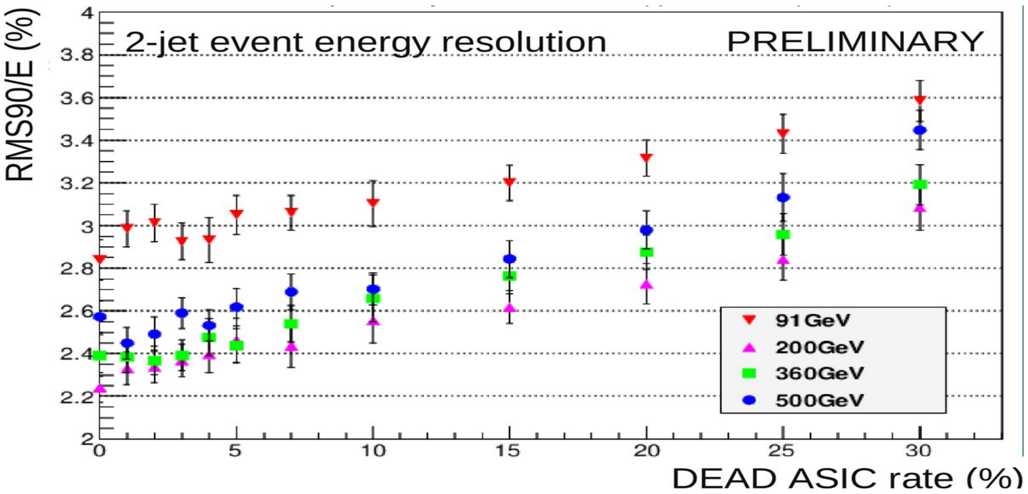
the single jet energy resolution after a simple dependent correction as a function of the guard ring thickness.

An ECAL average signal versus azimuthal angle. The loss in inter-sensor dead areas is visible (between barrel modules, barrel and endcap
and between the sensors, the latter depends on the guard ring).

Resilience


Single photon resolution
PRELIMINARY
10GeV
30GeV
50GeV
100GeV
dead rate(%)


91GeV
200GeV
360GeV
500GeV
2-jet event energy resolution
PRELIMINARY
Dead pixel rate (%)


RMS90/E (%)
2-jet event energy resolution
PRELIMINARY
91GeV
200GeV
360GeV
500GeV
DEAD ASIC rate (%)